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Hydrodynamic characteristics of a supercavitating vehicle's aft body

Xulong Yuan [a], Tao Xing [b,*]

[a] School of Marine Science and Technology, Northwestern Polytechnical University, Xi'an, Shaanxi 710072, China
[b] Department of Mechanical Engineering, University of Idaho, Moscow, ID 83844-0902, USA

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A B S T R A C T

The nonlinear and multi-factor-dependent characteristics of the hydrodynamic forces acting on the aft body of a supercavitating vehicle are investigated using computational fluid dynamics (CFD). The CFD model of natural supercavitating flow is first verified and validated upon the supercavitating flow around a cavitator in the shape of a circular disk. Then the model is used to simulate the supercavitating flows over a typical supercavitating vehicle model at different cavitation numbers σ and angles of attack (AOA) α. By analyzing the supercavitating flow patterns and hydrodynamic force curves, the hydrodynamic characteristics of the aft body and their forming mechanisms are revealed: (a) The normal force and pitch moment are mainly generated by the pressure difference between the windward side and leeward side of the cylinder section caused by asymmetrical reattaching of the supercavity. (b) The hydrodynamic coefficients depend on both σ and α nonlinearly. Free AOA α_{fr} and critical AOA α_{cr} are identified to model the nonlinearity of hydrodynamic force about AOA. (c) For the designated model, α_{fr} and α_{cr} depend on supercavitating flow patterns determined by σ. The simulation results and conclusions would be beneficial for more accurate dynamic modeling and control simulation for supercavitating vehicles.

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1. Introduction

By virtue of supercavitating drag-reduction effect, supercavitating vehicles can achieve a very high speed more than 200 knots, which is 3 times more than that of conventional underwater vehicles. The supercavitating projectiles can even achieve a speed greater than the sound speed in water (1450 m s^{-1}). Supercavitating phenomena also occur in the procedure of water-entry and water-exit of conventional underwater vehicles or aircrafts, which will cause the invalidity of the flight dynamic models developed for single phase flow. To accurately model and control the motions of supercavitating vehicles, it is necessary to investigate their hydrodynamic characteristics during supercavitating.

Hydrodynamic forces for supercavitating vehicles are much more complicated than those for convectional underwater vehicles. They are composed of forces acting on the cavitator, tail wings, and aft body which includes a cut cone, a cylinder and a nozzle as shown in Fig. 1. Because the cavitator has a constant wetted surface area during cruising, the correlation between the forces and angle of attacking α can be approximated using analytical formulas. Kiceniuk (1954) theoretically derived the formula to calculate forces acting on circular disk, which was experimentally validated by Savchenko (2001). The hydrodynamic forces acting on the tail wings are almost linear functions of the immersion length of wing span (Kirschner et al., 2002). Therefore the complexity of hydrodynamic forces of supercavitating vehicles mainly comes from the aft body which is the vehicle body excluding the cavitator and wings. The wetted surface area of aft body varies with both the cavitation number and angle of attack, which leads to the non-linear and multi-factor-dependent hydrodynamic characteristics. In most studies on dynamic modeling and motion control (Kirschner et al., 2002,2006; Kulkarni and Pratap, 2000; Vanek et al., 2007) of supercavitating vehicles, the Wagner planning theory developed by Logvinovich (1980) and its extensions were used to calculate the forces acting on the aft body. In this theory, the aft body is treated as a slender body planning on curved water surface unsteadily and the forces are calculated under the planning hypothesis. The theory is useful to understand the hydrodynamic characteristics of supercavitating vehicles and analyze preliminary motion control theoretically, but it is not accurate to be applied for real applications.

Some experimental and numerical investigations have been carried out to explore the hydrodynamic characteristics of supercavitating vehicles. Zhang et al. (2004) identified three typical flow patterns in a water tunnel experiment, namely, double-cavity, tail-closure, and wake-closure. Jiang et al. (2008) investigated the aft body hydrodynamic coefficients by the head-supported model test in a water tunnel. They measured the hydrodynamic forces at different cavity configurations, compared the results under zero and 1 degree AOA, and elucidated some relations between hydrodynamic forces and flow

* Corresponding author. Tel.: +1 208 885 9032; fax: +1 208 885 9031.
E-mail addresses: yuanxulong@nwpu.edu.cn (X. Yuan), xing@uidaho.edu (T. Xing).

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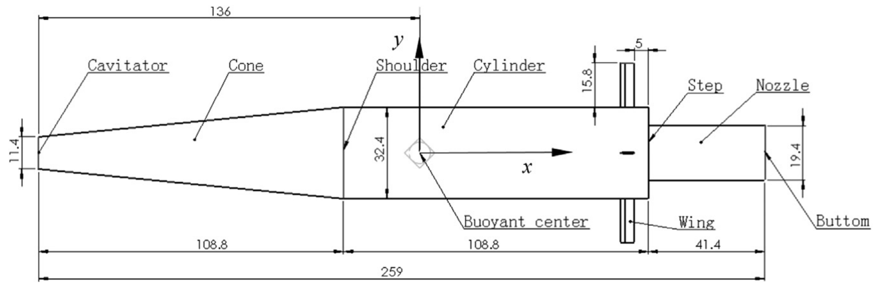

Fig. 1. Geometry of a supercavitating vehicle model.

patterns. Zhang and Zhang (2011) obtained the hydrodynamic characteristics of a supercavitating projectile using computational fluid dynamics (CFD), where only the wake-closure supercavitating flow pattern was investigated. They observed the existence of a free AOA up to which the aft body will not contact with the cavity and no normal force and pitch moment will be generated. Yuan et al. (2012) experimentally investigated the hydrodynamic characteristics of three kinds of supercavitating vehicles and observed the critical angle of attack and the "zero slope region", i.e., free AOA in this study. But this experimental study was performed under incomplete similarity due to the large aspect-ratio of the geometry.

As a summary, previous studies on the hydrodynamic forces obtained some basic knowledge about the hydrodynamic characteristics. Nonetheless, for the lack of fine increments of angle of attack, relatively large experimental uncertainty, and no quantitative solution verification and validation for CFD simulations, they did not provide a detailed analysis of hydrodynamic characteristics and their formation mechanism. The objective of this study is to use advanced CFD models to investigate those details via a typical supercavitating vehicle with rigorous solution verification and validation for supercavitating flow around the cavitator.

2. Geometry and simulation design

For the convenience of the future experimental study, a simplified typical small aspect-ratio supercavitating vehicle model was designed. It consists of five components, including a cavitator at front, a cut cone, a cylinder, four wedge-profile wings offset 90° to each other, and a nozzle, as shown in Fig. 1. The aft body is defined as the vehicle body without the cavitator and four wings. The unit in Fig. 1 is *mm*.

Simulations were carried at 16 angles of attack and 3 cavitation numbers, which result in a total of 48 simulations as summarized in Table 1. The variation of cavitation number is obtained by changing the outlet pressure while fixing the inlet velocity at 20 m s^{-1}.

The cavitation number σ is defined as

$$\sigma = \frac{p_o - p_v}{\frac{1}{2}\rho U_\infty^2} \tag{1}$$

where p_v is vaporization pressure of water, ρ is fluid density, U_∞ is the magnitude of inlet velocity, and p_o is the outlet pressure.

The angle of attack α is defined as

$$\alpha = \arctan\frac{v_y}{v_x} \tag{2}$$

where v_x is the axial velocity component and v_y is the velocity component along the y axis as shown in Fig. 1.

Table 1
Simulation cases.

Group number	σ	Pressure(Pa)	$\alpha/°$
1	0.055	1.45E+04	0.0, 0.2, …, 3.0
2	0.063	1.60E+04	0.0, 0.2, …, 3.0
3	0.065	1.65E+04	0.0, 0.2, …, 3.0

3. Computational method

3.1. Mathematical modeling

The supercavitating flows were simulated using the mixture multiphase flow model in ANSYS FLUENT 15.0. The equations for the mass and momentum conservation were solved to obtain the velocity and pressure fields. The standard $k-\varepsilon$ model with the standard wall function was adopted for turbulence closure, and Schnerr–Sauer cavitation model (Schnerr and Sauer, 2001) was used to model the mass transfer between the two phases. Governing equations are briefly summarized below, the readers can refer to Theory Guide of ANSYS FLUENT (2013) and Sunho Park et al. study (Park and Rhee, 2012) for additional details.

The continuum equation for mixture is

$$\frac{\partial}{\partial t}(\rho_m) + \nabla\cdot(\rho_m \vec{v}_m) = 0 \tag{3}$$

where $\vec{v}_m$ is the mass-averaged velocity:

$$\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_k}{\rho_m} \tag{4}$$

and ρ_m is the mixture density:

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \tag{5}$$

where α_k is the volume fraction of phase k, n is the number of phases.

The equation for the conservation of momentum can be written as

$$\frac{\partial \rho_m \vec{v}_m}{\partial t} + \nabla\cdot(\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla\cdot\left[\mu_m\left(\nabla\vec{v}_m + \nabla\vec{v}_m^{\,T}\right)\right] + \rho_m \vec{g} + \vec{F} \tag{6}$$

where p is the static pressure, $\vec{F}$ is a body force, and μ_m is the viscosity of the mixture:

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \tag{7}$$

For each phase, $\mu_k = \mu + \mu_t$. μ is the viscosity, and μ_t is turbulence viscosity. Once the Reynolds averaging approach for turbulence modeling is applied, the unknown term, i.e., the Reynolds stress term, is related to the mean velocity gradients by the

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